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## NEUROPSYCHOLOGY | RESEARCH ARTICLE

# Driving slow motorised vehicles with visual impairment—A simulator study

Christina Cordes<sup>1,2\*</sup>, Joost Heutink<sup>1,2</sup>, Karel A. Brookhuis<sup>1</sup>, Wiebo H. Brouwer<sup>1</sup> and Bart J.M. Melis-Dankers<sup>3</sup>

**Abstract: Purpose:** To compare different driving parameters between visually impaired people and normal sighted controls in a mobility scooter and microcar driving simulator.

**Materials and methods:** A mobility scooter and microcar driving simulator and different virtual environments were developed for the purpose of this experiment. Participants completed 4 drives in the microcar driving simulator and 8 drives in the mobility scooter driving simulator. Driving performance was compared between visually impaired and normal sighted participants, using the parameters speed, lateral position, time-to-collision, and number and type of collision.

**Results:** Visually impaired participants did not differ significantly from normal sighted controls with regard to speed and overall lateral position. In contrast, number of collisions was higher in visually impaired participants in almost all drives. Time-to-collision differed in some, but not all of the drives. Small obstacles with low contrast posed the highest risk of collision for impaired drivers.

**Conclusions:** The present findings showed that visually impaired participants were able to maintain a steady position on the street, but showed more difficulties in traffic situations that included obstacles and other traffic participants. Familiarity

### ABOUT THE AUTHOR

Christina Cordes is a clinical researcher at Royal Dutch Visio, Center of Expertise for blind and partially sighted people, and is currently undertaking her doctoral studies at The University of Groningen, the Netherlands. Her main research focus is on driving safety of visually impaired individuals in mobility scooters and other slow motorised vehicles.

### PUBLIC INTEREST STATEMENT

Individuals with visual impairment can face more difficulties in traffic situations than normal sighted individuals. In contrast to research on cars, there is not much research available on the use of slow motorised vehicles (e.g. mobility scooters, microcars) by visually impaired individuals. Mobility scooters in particular are important vehicles that help to maintain individuals' independence. Therefore, we investigated the driving safety of visually impaired participants in a mobility scooter and microcar driving simulator. We found that visually impaired participants were able to maintain a steady position on a winding road, but showed more difficulties in traffic situations that included obstacles and other traffic participants. Small obstacles with low contrasts (e.g. bollards) in particular posed a risk for collision. Familiarity with the driving tasks seemed to improve performance. These findings could be used to improve training facilities in rehabilitation and/or to make infrastructure design safer for the visually impaired.

with the driving tasks seemed to improve performance, however, further research is necessary to confirm this observation.

**Subjects:** Computer Science; Engineering & Technology; Neuropsychology; Health and Social Care; Occupational Therapy; Quality of Life

**Keywords:** low vision; mobility scooter; microcar; driving simulator; driving performance; rehabilitation

## 1. Introduction

Visual impairment can prevent humans from extracting essential visual information from the environment. Especially in traffic situations, visually impaired individuals face more challenges than sighted people (Owsley & McGwin, 2010; Szlyk, Seiple, & Viana, 1995). In cars, legal visual standards have been introduced to ensure safety for visually impaired individuals and other traffic participants. However, studies investigating the possibilities for maximizing participation reveal that some people with visual impairments can still drive safely despite not meeting the required legal standards (De Haan et al., 2014; Owsley & McGwin, 1999; Dow, 2011), and that abilities such as compensatory strategies need to be considered (Coeckelbergh et al., 2004).

In contrast to ordinary motor vehicle traffic, the effect of visual impairment on driving slow motorised vehicles has hardly been investigated. Slow motorised vehicles are defined as motor vehicles with a maximum speed of 45 km/h (28 mph). This category includes vehicles such as mopeds, microcars, and mobility scooters. The focus of the present study is on the latter two vehicles (Figure 1). Mobility scooters are mobility aids especially designed for the physically disabled and are permitted to be driven both indoors and outdoors on pavements, cycle lanes, and roads. They are open vehicles with three, four, or five wheels and have a speed range of approximately 5–15 km/h (3–10 mph). Microcars are small cars with a speed limit of 45 km/h that follow the traffic rules of mopeds (e.g., driving in urban traffic, but prohibited on motorways). The European driving licence category AM needs to be passed to be allowed to drive microcars. However, in the Netherlands, for both microcars and mobility scooters, legal visual standards do not exist.

Previous studies have shown that visual impairment affects driving performance in mobility scooters (Cordes, Heutink, & Brookhuis et al., 2018; Cordes, Heutink, & Tucha et al., 2017; Nitz, 2008). However, these findings do not imply that people with visual impairments cannot participate safely in traffic. People with low visual acuity have been shown generally to be safe drivers, whereas visual field defects seem to impact driving performance more than low visual acuity (Cordes et al., 2017). Driving performance in the studies by Nitz (2008) and Cordes et al. (2017) was assessed with on-road driving tests, which may have limited standardization and objectivity. To increase standardization and objectivity, specially equipped driving simulators could be used to study driving performance, especially in vulnerable patient groups (Medeiros et al., 2012). In

**Figure 1.** Microcar (left, photo from Garage Vink Astén. Obtained from <https://www.garagevink.nl/brommobielcenter-brabant/voorraad-brommobielen/microcar-m-go-brommobiel/>, July 2017) Mobility scooter (right).



contrast to on-road assessments, researchers can control environments in driving simulators, explore driving performance in greater detail and more objectively, and provide safe training conditions (De Winter, Van Leeuwen, & Happee, 2012). Driving simulations cannot exactly replicate real-world performance (Mullen, Charlton, & Devlin, 2011), but in several studies it has been shown that performance in driving simulators is valid in the sense of revealing the same pattern of results as found in on-road driving performance (Bedard et al., 2010; Lee, 2003, Mayhew et al., 2011; Underwood, Crundall, & Chapman, 2011).

A number of studies explored driving performance of visually impaired individuals in car driving simulators. Szlyk, Brigell, & Seiple (1993) showed that visually impaired participants displayed significantly more lane boundary crossings and more variability in lateral position compared to normal sighted participants. In a later study, Szlyk et al. (2005) investigated driving performance in glaucoma patients compared to normal sighted controls and showed that the number of collisions with other traffic participants was significantly correlated to visual field loss, but not to low visual acuity or contrast sensitivity. These results confirm an earlier observation that participants with retinitis pigmentosa had more collisions compared to normal sighted controls in a driving simulator task (Szlyk et al., 1992). Coeckelbergh et al. (2002) showed that participants with central visual field defects drove at lower speeds and exhibited a shorter time-to-collision with a lead car compared to participants with peripheral visual field defects and normal sighted controls, whereas participants with peripheral visual field defects showed more variation in lateral position compared to other participants. Visual field defects did not lead to significantly more collisions in the driving simulator task.

To the best of our knowledge, no study has yet investigated driving performance of visually impaired people in a driving simulator for slow motorised vehicles. A review by Erren-Wolters et al. (2007) suggests that virtual reality can be useful to improve the use of electric mobility devices. Jannink et al. (2008) evaluated a mobility scooter training programme using a driving simulator and showed that both on-road training and driving simulator training yielded improved driving skills. The present study aims to examine driving performance of visually impaired individuals in a standardized manner by studying parameters such as lateral position, speed, time-to-collision, and number and type of collision in a driving simulator. For this purpose, virtual environments were created for mobility scooters and microcars. Research questions were whether (1) visually impaired individuals show poorer lateral position control than normal sighted controls, (2) visually impaired participants have shorter time-to-collision values than normal sighted controls, (3) visually impaired people have more collisions compared to normal sighted controls, and (4) certain types of obstacles impose a particular challenge for the (visually impaired) participants. Since visual functioning in itself has not been shown to be a good predictor of on-road driving performance in cars (Coeckelbergh et al., 2004; De Haan et al., 2014; Owsley & McGwin, 1999; Dow, 2011), we do not expect a strong relationship between visual impairment and driving performance in the slow motorised vehicle driving simulator either. Therefore, this study does not aim at establishing visual standards for slow motorised vehicles, but rather intends to explore areas that show opportunities for training or technically assisting visually impaired individuals.

## 2. Method

The experiment was conducted at the University Medical Center Groningen (UMCG), the Netherlands, and was part of the project Mobility4all, investigating the influence of low vision on traffic safety in slow motorised vehicles. A driving simulator with two mock-ups and different driving environments was developed for the purpose of this study (ST Software Simulator Systems, Groningen, the Netherlands).

### 2.1. Participants

In total, 94 normal sighted controls and participants with visual impairment caused by ocular pathology between 50 and 70 years of age took part in the experiment. A number of participants had to be excluded from analysis due to driving simulator sickness or technical difficulties,

resulting in different sample sizes per simulator drive (see Figure 3 for detailed information about sample sizes). Visual impairment included low visual acuity (Snellen: 20/200–20/50 or 6/60–6/15; LogMAR: 2–0.4), visual field defects, or a combination of both (for more detailed descriptions of inclusion criteria and visual information, see Cordes et al., 2017). There were no significant differences between visually impaired and normal sighted participants with regard to age and general cognitive functioning (Table 1). Normal sighted controls had significantly more driving experience (all types of motorised vehicle except for mobility scooters) than visually impaired participants ( $t(92) = 4.106, p < 0.001$ ). No differences could be found between male and female participants with regard to age, cognitive functioning and driving experience. All participants completed real-life mobility scooter training and assessment before driving in the simulator environments. The experiment was approved by the Ethical Committee Psychology of the University of Groningen, the Netherlands, according to the Declaration of Helsinki. All participants provided written informed consent.

## 2.2. Driving simulator

The driving simulator consisted of a microcar or mobility scooter mock-up that stood in front of three big screens (Figure 2). The screens were arranged in a U-shape around the mock-ups, enabling a 180 degree view of the traffic environment. A fixed-based mock-up was used to assess driving performance in microcars. The mock-up consisted of a standard open car cabin, including an adjustable seat, steering wheel, indicators, pedals (accelerator and brake), a hand brake, and an automatic gear system. Maximum speed limit was 45 km/h (the legal speed limit of microcars). Distance from the steering wheel of the mock-up to the middle screen was 110 cm. The mobility scooter driving simulator mock-up was a real mobility scooter that was technically adapted and connected to the simulation PCs by sensors for steering and switches. It was positioned in front of the middle screen at a distance of 80 cm from the front of the mobility scooter. Maximum speed was 15 km/h (the physical speed limit of the mobility scooter). The mock-ups were connected to three PCs running the software for the driving simulation. The simulation software calculated all vehicle movements in the simulated world and the counterforces that acted on the steering in the vehicle model.

The screens were operating at a frequency of 60 Hz. The middle screen had a resolution of  $1920 \times 1080$ , the side screens had a resolution of  $1024 \times 768$ . The dimensions of the projections were  $200 \times 110$  cm. The software generated sounds for the propulsion motor and the motor sounds of the surrounding traffic, which were reproduced by two speakers.

## 2.3. Driving environments

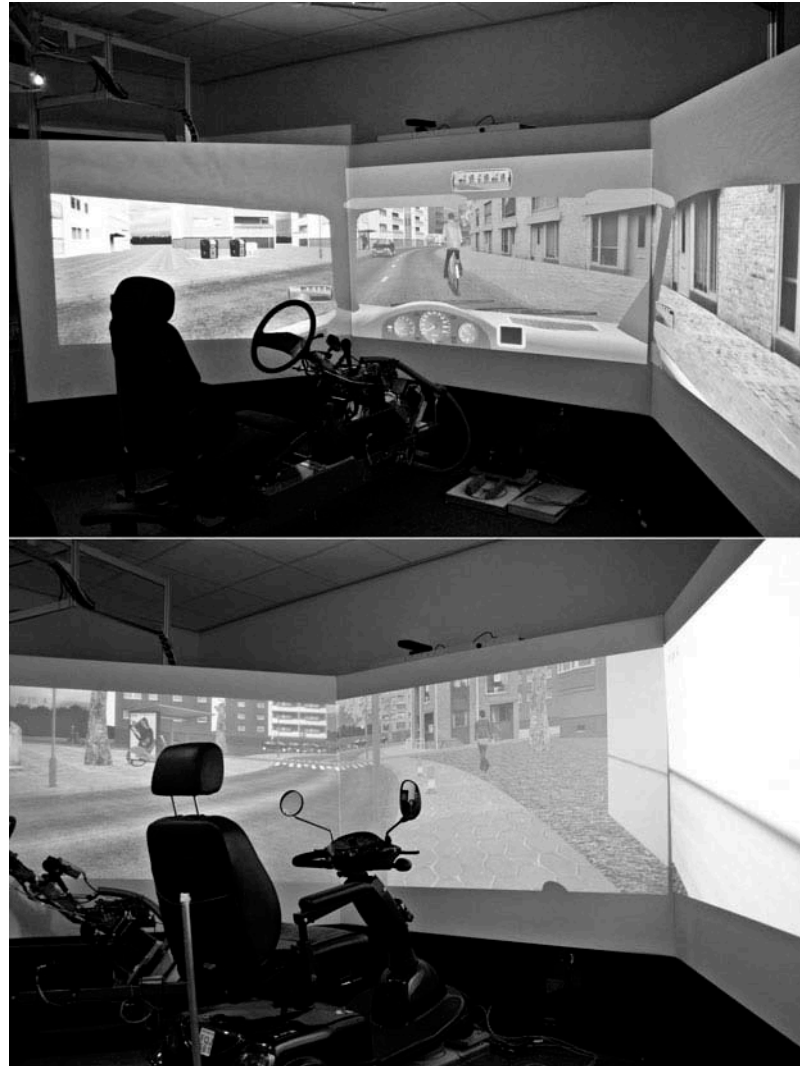
The virtual environments were especially designed for the purpose of this experiment. Three environments were developed for the microcar and mobility scooter simulator using ST simulation software (ST Software Simulator Systems, Groningen, the Netherlands) to explore driving performance under different conditions: (1) Microcar driving on street (max. 45 km/h, 6 m wide), (2) Mobility scooter driving on pavement (max. 5 km/h, 2 m wide), and (3) Mobility scooter driving on

**Table 1. Participants' characteristics**

	Visually impaired participants ( $n = 57$ )	Normal-sighted controls ( $n = 37$ )
Female	20	14
Male	37	23
Age (mean $\pm$ SD)	61.2 ( $\pm$ 7.7)	61.0 ( $\pm$ 5.5)
MMSE <sup>a</sup> (mean $\pm$ SD)	28.07 ( $\pm$ 1.62)	28.43 ( $\pm$ 1.39)
Driving experience (mean years $\pm$ SD)	26.5 ( $\pm$ 14.9)	38.1 ( $\pm$ 10.5)

<sup>a</sup>Mini Mental Status Examination, a screening tool for general cognitive functioning. A score below 24 indicates cognitive impairment

**Figure 2. Microcar (above) and mobility scooter (below) driving simulator.**



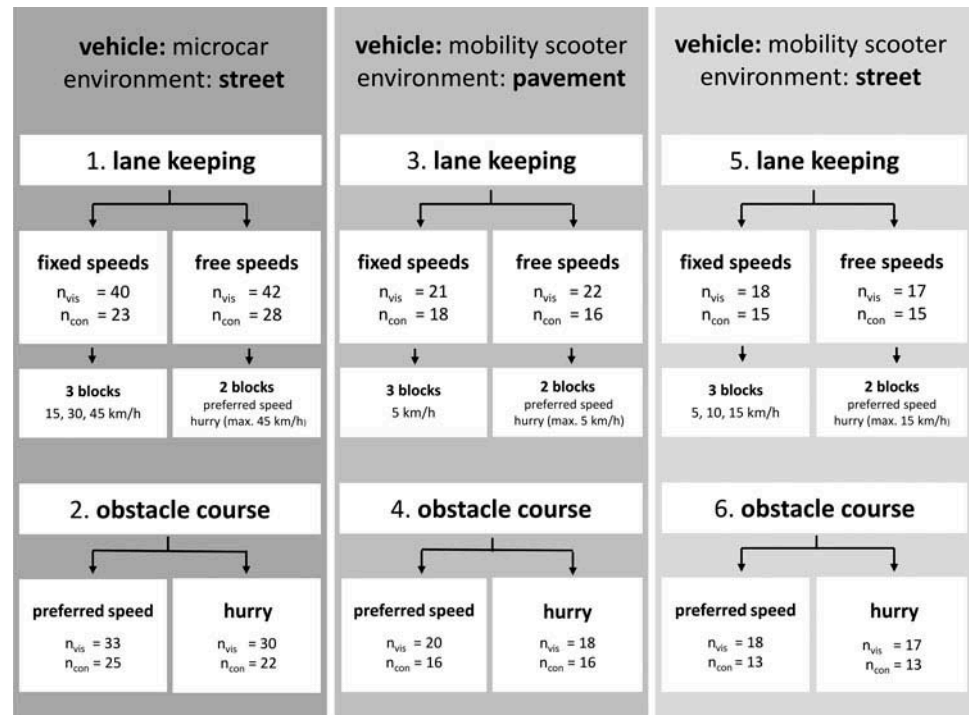
street (max 15 km/h, 6 m wide). These environments were further subdivided into two different short driving courses to measure different aspects of driving performance: lane-keeping courses and obstacle courses (Figure 3). Each course took approximately 2–3 min.

The lane-keeping courses consisted of a winding road with a relatively plain surrounding and no intersections. Except for a number of oncoming cars on the street, there were no obstacles present. The main purpose of the lane keeping courses was to measure lateral position control (SDLP: standard deviation lateral position) at different speeds. The two lane keeping courses came with two instructions: In the first drive speed was fixed and was divided into 3 blocks in which speed increased in steps throughout the course (except for mobility scooter drive on pavement, where speed remained constant at 5km/h), in the second drive participants were asked to choose their own preferred speed (block 1) or drive as fast as possible (block 2).

The obstacle courses consisted of a city environment with 4 intersections (where participants had to give right of way) and a number of static obstacles and dynamic traffic agents. The software generated traffic agents that moved autonomously through the environments.



**Figure 3. Overview of the different simulator drives.**



Traffic was controlled by a script that regulated all intended traffic interactions and conflicts during the simulator drive. Static obstacles were created with four different characteristics: (1) small and low contrast (e.g. grey bollard), (2) small and high contrast (e.g. coloured bollard), (3) big and low contrast (e.g. grey parked car), and (4) big or high contrast (e.g. coloured bin). Traffic agents (e.g., cars, trucks, bicycles, pedestrians) were divided into three categories: (1) coming from the left at an intersection, or (2) coming from the right at an intersection, or (3) had to be overtaken (both overtaking slow traffic agents travelling in the same direction and passing traffic agents approaching from the opposite direction). The number and type of static obstacles were evenly distributed for the different simulator drives using a  $2 \times 2$  matrix (two small, low-contrast obstacles, two small, high-contrast obstacles, two big, low-contrast obstacles, and two big, high-contrast obstacles per drive). Likewise, the number and type of traffic agents were balanced for the different drives (two traffic agents from the left, two traffic agents from the right, two traffic agents to overtake). Only in the last drives (mobility scooter on street) were more than two obstacles or traffic agents implemented for certain categories to avoid predictability.

The goal of the obstacle courses was to record the number of collisions and time-to-collision (TTC: the time that is left before a collision takes place if speed and direction are not changed) towards obstacles and other traffic agents. As in the lane-keeping courses, the obstacle courses were split into two drives according to the following instructions: During the first drive, participants were asked to drive with a preferred speed, during the second drive participants were asked to drive as fast as possible without neglecting safety.

## 2.4. Procedure

Participants completed 12 drives in total, starting with four drives in the microcar simulator (the two lane-keeping courses were completed first, followed by the two obstacle courses), four drives in the mobility scooter simulator on the pavement and finally four drives in the mobility scooter on the street (Figure 3). Participants were instructed to operate the vehicles as they normally would in traffic and to obey the traffic rules. The specific instruction for the lane-keeping courses was to adapt a safe position on the road and to keep that position during the drive. For the free-speed conditions,

participants were asked to start driving with their preferred speed. Halfway through the drive they were prompted to drive as fast as they could whilst staying safe (hurry) For the obstacle courses, participants were instructed to avoid collisions with obstacles and other traffic participants adapting their preferred speed (part 1) or driving as fast, yet safe, as they could (hurry, part 2).

A 5-minute break was taken between the microcar and mobility scooter simulator tasks and mock-ups were rearranged. Before proceeding with the mobility scooter driving simulator tasks, participants completed a practice drive in the simulator, because an informal pilot study had revealed that judging distances might be challenging in these simulations. Because simulator sickness is a common phenomenon in driving simulator research, participants were informed about the symptoms of simulator sickness and assured that they could stop the task at any time. To monitor the well-being of the participants, the Simulator Sickness Misery Scale (MISC) was taken after each drive (Bos et al., 2013). The MISC is an 11-point scale to measure the degree of simulator sickness symptoms (feeling unwell, dizziness, actually feeling sick). A score  $>6$  was an indicator for light sickness and served as an objective marker in this experiment to stop the drives.

### 2.5. Statistical analysis

Dependent variables were the outcome measures of the driving simulation: speed, standard deviation lateral position (SDLP), minimum time-to-collision (TTC), and number and type of collisions. SDLP was measured as the deviation from the centre line, whereas TTC was measured using the speed of the driver and the distance towards obstacles or other traffic participants. TTCs larger than 2 s were seen as safe. A collision was recorded when TTC reached zero.

For the lane-keeping courses, speed and SDLP were calculated per block per drive. Since the assumption of normality was not met, visually impaired participants were compared to normal-sighted controls using non-parametric tests (Mann-Whitney U). For the obstacle courses, the number of collisions and the TTCs for static and dynamic (crossing and to be overtaken) obstacles were compared between visually impaired and normal sighted participants. Maximum value of the time-to-collision was 4 s. Mann-Whitney U tests were used for these comparisons. Furthermore, the relative risk of visually impaired and normal sighted participants to collide ( $TTC = 0$ ) or nearly collide ( $TTC < 0.5$ ) with a certain obstacle group was calculated. For this purpose, obstacles were categorized according to their characteristics into static small objects with either high or low contrast, static large objects with high or low contrast, moving objects from the left, moving objects from the right, or moving objects that had to be overtaken. The number of (near-)collisions with these object categories were accordingly calculated and, depending on how many drives a respective participant completed, the chance of collision with a certain obstacle category was obtained. The mean chance of collision was then calculated separately for the group of visually impaired participants and controls.

## 3. Results

### 3.1. Lateral position and speed

In the lane-keeping drives (6 in total), lateral position control of visually impaired participants and normal sighted controls did not significantly differ overall. Only in two blocks visually impaired participants showed significantly larger variability in their lateral position than controls: the first block of the fixed-speed lane-keeping drive of the microcar environment (speed: 15 km/h;  $t(61) = 2.25$ ,  $p < 0.05$ ) and the first block of the fixed lane-keeping drive of the mobility scooter street environment (speed: 5 km/h;  $t(31) = 2.33$ ,  $p < 0.05$ ). Noticeable is the large inter-individual variability in the SDLP scores, especially amongst the visually impaired participants (Table 2). With regards to speed, visually impaired participants did not drive significantly slower than normal sighted controls in any conditions. On the mobility scooter drive on the street, both visually impaired participants and normal sighted controls drove at the highest possible speed.



**Table 2. Mean SDLP (SD) and speeds for the different lane-keeping drives**

Drive		Lateral position	Speed (km/h)	
		SDLP (cm)	Preferred speed	Hurry
Microcar	VI**	47.0 (11.7)	–	–
(fixed speed)	Controls	39.1 (11.9)	–	–
Microcar	VI	46.2 (16.1)	26.3 (7.1)	37.4 (9.5)
(free speed)	Controls	41.2 (12.5)	27.7 (7.3)	39.3 (9.2)
MS* pavement	VI	22.0 (25.4)	–	–
(fixed speed)	Controls	12.1 (9.1)	–	–
MS pavement	VI	34.5 (19.5)	11.8 (2.0)	14.7 (1.4)
(free speed)	Controls	28.1 (11.0)	11.6 (3.0)	14.8 (1.6)
MS street	VI	30.1 (22.8)	–	–
(fixed speed)	Controls	22.8 (7.8)	–	–
MS street	VI	39.8 (11.7)	15.2 (1.2)	16.2 (0.2)
(free speed)	Controls	35.8 (14.3)	15.0 (1.5)	16.2 (0.2)

\* MS = Mobility Scooter

\*\* VI = visually impaired

### 3.2. Number of collisions

Except for the first drive in the mobility scooter drive on the pavement, visually impaired participants have significantly more collisions compared to normal sighted controls (Table 3). Figure 4 shows that visually impaired participants have most collisions in the first microcar drive, and least collisions on the mobility scooter drive on the street. In addition to that, even though participants were asked to drive faster in the second condition of the environments, fewer collisions can be observed for this instruction in all three environments. The relative difference between visually impaired and normal sighted participants appears to be largest in the first drive of the microcar driving simulator.

### 3.3. Time-to-collision

For both visually impaired and normal sighted participants, the average TTC of all obstacle groups combined is larger than 2.5 s and thus cannot be classified as risky. A significant difference in

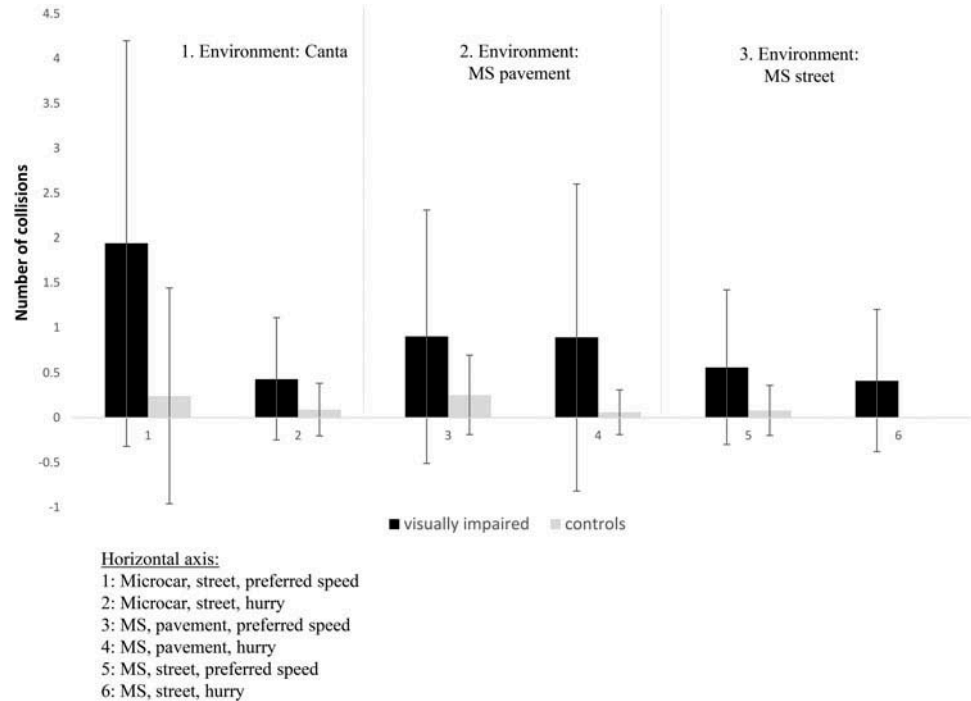
**Table 3. Number of collisions of visually impaired and normal sighted participants in the different drives**

Drive	Group	n	Mean	SD	Median	Test	p
Microcar	VI**	33	1.94	2.26	1.0	U = 198.5	< 0.001
(free speed)	Controls	25	0.24	1.2	0.0		
Microcar	VI	30	0.43	0.68	0.0	U = 247.0	0.036
(hurry)	Controls	22	0.09	0.29	0.0		
MS pavement	VI	20	0.90	1.41	0.0	U = 120.0	0.134
(free speed)	Controls	16	0.25	0.44	0.0		
MS pavement	VI	18	0.89	1.71	0.0	U = 103.5	0.048
(hurry)	Controls	16	0.06	0.25	0.0		
MS* street	VI	18	0.56	0.86	0.0	U = 79.5	0.050
(free speed)	Controls	13	0.08	0.28	0.0		
MS street	VI	17	0.41	0.79	0.0	U = 78.0	0.036
(hurry)	Controls	13	0.00	0.00	0.0		

\* MS = Mobility Scooter

\*\* VI = visually impaired

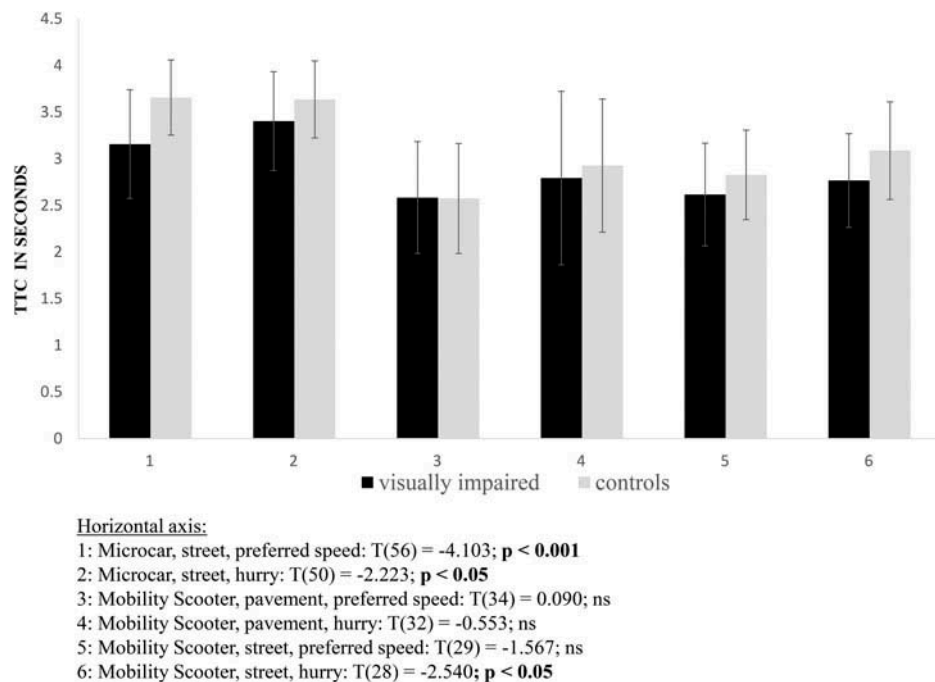
**Figure 4. Mean number of collisions per drive (error bars represent standard deviations).**



overall TTC between visually impaired participants and controls in the microcar simulator drives and the mobility scooter street drive could be found (hurry; Figure 5).

With regard to static objects, average TTCs are also long for both visually impaired and normal sighted participants (Table 4). Visually impaired participants show significantly shorter TTCs on the microcar street drive (preferred speed;  $T(56) = -4.746$ ;  $p < 0.001$ ) and the mobility scooter street drive

**Figure 5. Mean TTC in seconds of all obstacle groups combined for the different drives (error bars represent standard deviations).**



**Table 4. Mean (SD) TTC of visually impaired and normal sighted participants in the different drives**

Drive	Group	n	TTC static (s)		TTC crossing (s)		TTC overtake (s)	
			Mean (SD)	Median	Mean (SD)	Median	Mean (SD)	Median
Microcar	VI**	33	2.82 (0.71)	2.94	3.68 (0.34)	3.68	2.97 (0.70)	2.97
(free speed)	Controls	25	3.56 (0.34)	3.63	3.96 (0.17)	4.00	3.45 (0.70)	4.00
Microcar	VI	30	3.25 (0.36)	3.28	3.75 (0.32)	3.85	3.21 (0.91)	3.52
(hurry)	Controls	22	3.42 (0.46)	3.57	3.89 (0.16)	4.00	3.60 (0.62)	3.94
MS pavement	VI	20	2.83 (0.41)	2.94	3.01 (0.54)	2.97	1.91 (0.85)	1.79
(free speed)	Controls	16	2.55 (0.32)	2.55	3.30 (0.51)	3.26	1.87 (0.94)	2.23
MS pavement	VI	18	2.69 (0.78)	2.75	3.18 (0.77)	3.35	2.51 (1.24)	3.06
(hurry)	Controls	16	2.68 (0.71)	2.72	3.40 (0.47)	3.55	2.70 (0.96)	3.03
MS* street	VI	18	2.78 (0.50)	2.64	3.50 (0.54)	3.62	1.57 (0.61)	1.42
(free speed)	Controls	13	3.12 (0.37)	3.21	3.50 (0.45)	3.64	1.86 (0.62)	1.68
MS street	VI	17	2.72 (0.37)	2.77	3.40 (0.40)	3.38	2.18 (0.74)	1.94
(hurry)	Controls	13	2.77 (0.32)	3.72	3.54 (0.36)	3.59	2.95 (0.89)	3.23

\* MS = Mobility Scooter

\*\* VI = visually impaired

(preferred speed;  $U = 68.0$ ;  $p = 0.05$ ), and a significantly longer TTC on the mobility scooter pavement drive (preferred speed;  $U = 88.5$ ;  $p < 0.05$ ) compared to normal sighted controls. Concerning crossing traffic agents, visually impaired participants had shorter TTCs compared to normal sighted controls on the microcar street drive (preferred speed;  $U = 171$ ;  $p < 0.001$ ) and mobility scooter pavement drive (preferred speed;  $U = 98.5$ ;  $p = 0.50$ ). Last, regarding moving traffic agents participants had to overtake, visually impaired participants had significantly shorter TTCs in the microcar street drive (preferred speed;  $U = 235.5$ ;  $p < 0.05$ ) and the mobility scooter street drive (hurry;  $U = 55.0$ ;  $p < 0.05$ ).

### 3.4. Type of collisions

Analysis of the different obstacles groups revealed that most collisions took place with small, low-contrast objects (Table 5). Controls had fewer collisions compared to visually impaired participants. The elevated risk of collision for visually impaired participants compared to normal sighted controls is especially visible for static, small objects with low contrast and for all types of moving objects.

Furthermore, in Table 5, it is shown that visually impaired individuals more often come critically close to objects ( $TTC < 0.5$ ) than normal sighted controls, except for high-contrast objects. Participants with visual impairment who are in this critical range, end up colliding more often with objects, whereas normal sighted controls appeared to be able to prevent collisions despite their critical TTC. However, the probability of collision with any type of static and moving objects is low in both visually impaired and normal sighted participants. Around 30% of the visually impaired participants never had a  $TTC < 0.5$ .

## 4. Discussion

To the best of our knowledge, this is the first driving simulator study comparing driving performance of visually impaired and normal sighted people in slow motorised vehicles. The virtual driving environments were specially designed to answer the questions of this study. Parameters measured included lateral position, speed, time-to-collision, and number and type of collisions. It was found that visually impaired participants were generally able to control vehicle position on a winding road, but displayed more risky driving behaviour than normal sighted controls when presented with obstacles or when interacting with other traffic participants. Results are generally in accordance with earlier conducted research within this patient sample. In a study by Cordes et al. (2017), visually

**Table 5. Mean percentage of participants who collide with or come critically close to obstacles of the different obstacle categories**

Parameter		Static small LC*	Static small HC**	Static big LC	Static big HC	Moving left	Moving right	Moving front
Near-collisions + collisions (TTC<0.5)	Controls	12%	12%	11%	11%	1%	0.6%	8%
	VI***	25%	10%	13%	9%	4.4%	1.3%	9%
	VI/ controls	2.08	0.83	1.18	0.82	4.40	2.17	1.13
Collisions (TTC = 0)	Controls	4%	0%	0%	0%	1%	0.3%	1%
	VI	15%	4%	5%	5%	4%	1%	4%
	VI/ controls	3.75	0.04	0.05	0.05	4.00	3.33	4.00
Near-collisions (0.5>TTC>0)	Controls	8%	12%	11%	11%	0%	0.3%	7%
	VI	10%	6%	8%	4%	0.4%	0.3%	5%
	VI/ controls	1.25	0.50	0.73	0.36	0.004	1.00	0.71

\*LC = low contrast

\*\*HC = high contrast

\*\*\*VI = visually impaired

The first three rows show the percentages of participants with a TTC below 0.5 (including collisions), the next three rows show the percentage of participants who actually collided, and the last three rows show the percentage of participants who came critically close to objects without colliding

impaired participants demonstrated sufficient lateral position control in a mobility scooter on-road test, but were more often involved in risky traffic situations compared to normal sighted controls.

#### 4.1. Lateral position and speed

Visually impaired participants showed little statistical differences in lateral position control compared to normal sighted controls, although the large variation indicated that visually impaired participants had less lateral position control on an individual level. This observation is in accordance with research by Coeckelbergh et al. (2002), who showed that visually impaired people, in particular people with peripheral visual field defects, displayed more variation in their lateral position. Furthermore, we expected visually impaired participants to reduce their speed due to their impairment, which was not confirmed by the results. This suggests that visually impaired participants did not choose to compensate for their impairment by adapting their speed and dared to drive as fast as participants without any visual impairment.

#### 4.2. Number and type of collisions

The results of the present study are in line with studies that have shown that participants with visual impairment have more collisions in a dynamic car driving simulation than normal sighted controls (Szlyk et al., 1993, 2005). Visual field problems in particular were related to risk of collision in these studies. Future studies need to investigate the role of different types of impairment on safe driving performance in slow motorised vehicles as our sample size was too low to allow for an in-depth analysis between the groups with different visual impairment. Interestingly, the number of collisions was lower for the second drive in the same environment (hurry) compared to the first part (preferred speed), suggesting better performance with more familiarity. This is especially visible in the microcar simulator, where visually impaired participants show a highly reduced number of collisions in the second drive. Research suggests that executive functioning and thus the ability to adapt to novel task decreases with age (Lowe & Rabbitt, 1997). Due to their impairment, visually impaired participants in this study might have had extra difficulties initially adapting to the driving simulator task and accordingly improved on the second drive.

As should be expected, the type of objects participants collided with most were small objects with low contrast, i.e. grey bollards or branches on the street. For visually impaired participants especially, these types of objects posed a larger risk of collision. The observation that the risk of collision is particularly elevated in small, low-contrast obstacles, but not in small, high-contrast ones, confirms earlier research revealing poor visibility of obstacles and road markings are the main causes of one-sided collisions in cyclists (Fabriek, De, & Schepers, 2012; Schepers & Den Brinker, 2011). The authors of this study advocated minimizing unnecessary use of road obstacles and to maximize visibility of necessary objects by using high-contrast colours. In addition, moving traffic agents also created a greater risk for visually impaired participants. This finding stresses the importance of increasing awareness of potential moving hazards on the road in visually impaired drivers. Future studies could investigate if a certain type of training, e.g., scanning training for people with visual field defects, could increase attentiveness towards other traffic participants at crossings. Since visually impaired participants did not show any reduction in their chosen speed, it would also be interesting to investigate whether a reduction in speed would have resulted in fewer collisions.

#### **4.3. Time-to-collision**

Analysis of the time-to-collision did not suggest a highly elevated risk of collision for visually impaired and normal sighted participants. One-third of the visually impaired participants never got critically close to either objects or traffic agents. Differences between visually impaired participants and normal sighted controls were observed particularly in the first condition of the drives (preferred speed). This again suggests that visually impaired individuals need more time to adapt to a new driving environment. For rehabilitation, this stresses the importance of sufficient familiarization with the driving environment and ample training time. Future studies should further investigate the effect of familiarity and predictability of the driving environment on mobility scooter driving safety. Earlier studies have shown that familiarity with the environment can lead to fewer collisions, since more attentional capacity is available for hazard detection (Martens & Fox, 2007; Schepers & Den Brinker, 2011). In addition, (visually) impaired drivers tend to prefer driving in more familiar environments (Owsley & McGwin, 2010), suggesting that they are aware of difficulties in unfamiliar situations and choose to compensate for it.

#### **4.4. Strengths and limitations**

To the best of our knowledge, no other study has yet created driving simulations for slow motorised vehicles that are particularly tailored to measure driving performance of visually impaired people. Despite creating standardization and objectivity, our driving simulators come with a number of disadvantages. One of these is the scope for generalization of the test results. In the present study, estimating distances from obstacles and traffic agents in the mobility scooter driving simulator appeared to be difficult for participants, despite a practice drive every participant had to complete beforehand. In real traffic, mobility scooter users can manoeuvre their vehicle around obstacles by directly looking down. However, due to the set-up of the driving simulator, this information was not accessible in the virtual environments. Especially in the mobility scooter environments on the pavement, where the space to avoid collision is limited compared to the other environments, incorrect judgement of distances could have led to an inflated number of collisions for both visually impaired and normal sighted participants. In addition, the steering of the mobility scooter was very sensitive. Although this difficulty did not seem to have a negative impact on lateral position control in participants with visual impairment, it might have contributed to the difference found in collisions, since more steering skills were required to manoeuvre around the different obstacles.

Furthermore, participants in the present study suffered unexpectedly severely from driving simulator sickness. More than half of the participants both the group of visually impaired participants and normal sighted controls stopped with the driving simulator tasks at some point (visually impaired participants did not differ statistically significant in their drop-out rate from normal sighted controls). Relatively more female participants dropped out in total as a result of simulator sickness compared to male participants (approximately 94% versus 53%). Simulator sickness is a negative side effect of

driving simulator studies, resulting in symptoms such as dizziness, headaches, or nausea (Brooks et al., 2010). Simulator sickness may not only lead to missing data, but may also have an influence on the validity of the driving task (Stoner & Fisher, 2011). To minimize the influence of driving sickness symptoms on driving performance in the present study and to secure the participants' well-being, we monitored the participants' symptoms strictly and stopped the driving simulations before symptoms increased. This, however, resulted in much smaller sample sizes, as fewer participants completed the different driving courses. Due to the small sample sizes, we were not able to analyse visually impaired participants according to their type of visual impairment and we cannot draw any conclusions about the performance of participants with different visual impairments. In addition, differences between males and females could not be analysed and might be an interesting target for future studies.

Last, the driving simulator tasks all had a similar design to maximize comparability between the different drives. This similarity could have resulted in a certain predictability and learning effect in later drives, which could have been the reason for fewer collisions and decreased time-to-collisions in the second part of the driving courses. However, the improved performance also highlights the fact that participants were able to adapt quickly, which could be an interesting observation for rehabilitation purposes.

## 5. Conclusion

Visually impaired individuals are able to keep a safe position on winding roads and pavements at variable speeds (5–45 km/h), but perform less safely compared to normal sighted controls when interacting with other traffic participants and obstacles on the road. Reduced contrast in the environment increases risk of collision more than the size of the object. Nevertheless, these findings do not suggest that visually impaired individuals are unfit to drive slow motorised vehicles, since total numbers of collisions are still low. Furthermore, familiarity with the environment appears to improve driving performance. The findings could be used to improve training facilities in rehabilitation and infrastructure design. Further research is needed to confirm the role of familiarity and/or investigate different types of visual impairment in a driving simulator setting.

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## Competing interests

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